Tests of isospin symmetry breaking at $\phi(1020)$ meson factories

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Abstract

In a model of isospin symmetry breaking we obtain the $(e^-e^+ \to \pi^-\pi^+)$ amplitude Q and the isospin $I = 0$ and $I = 1$ relative phase ψ at the $\phi(1020)$ resonance in aproximate agreement with experiment. The model predicts $\Gamma(\phi \to \omega\pi^0) \approx 4 \cdot 10^{-4}$ MeV. We have also obtained $\Gamma(\phi \to \eta'\gamma) = 5.2 \cdot 10^{-4}$ MeV. Measuring this partial width would strongly constrain η-η' mixing. The branching ratios BR of the isospin violating decays $\rho^+ \to \pi^+\eta$ and $\eta' \to \rho^\pm\pi^\mp$ are predicted to be $BR(\rho^+ \to \pi^+\eta) = 3{\cdot}10^{-5}$ and $BR(\eta' \to \rho^\pm\pi^\mp) = 4{\cdot}10^{-3}$, respectively, leading to $BR[\phi \to \rho^\pm\pi^\mp \to (\pi^\pm\eta)\pi^\mp \to (\pi^\pm\gamma\gamma)\pi^\mp] = 10^{-6}$ and $BR[\phi \to \eta'\gamma \to (\rho^\pm\pi^\mp)\gamma] = 2 \cdot 10^{-6}$.

1. Introduction

It is generally belived that electromagnetic interactions and the mass differences of u and d quarks are the sources of the breaking of isospin symmetry [1]. Both lead, among other things, to the mixing of the isospin $I = 0$ and $I = 1$ members of the $SU(3)_f$ flavor nonets. The present paper deals with isospin symmetry violating meson decays that proceed via $\pi^0 - \eta$, $\pi^0 - \eta'$, $\omega - \rho^0$ and $\phi - \rho^0$ mixings. Well–known examples are the isospin–forbidden decays $\eta \to 3\pi$ (the main decay channel of the η) and $\psi' \to \psi\pi^0$ [2]. We concentrate on the decays $\phi \to \pi^+\pi^-$, $\phi \to \omega\pi^0$, $\rho^\pm \to \pi^\pm\eta$ and $\eta' \to \rho^\pm\pi^\mp$ that can thoroughly be investigated at ϕ meson factories. This is obvious for $\phi \to \pi^+\pi^-$ and $\phi \to \omega\pi^0$. Since the ϕ decays into $\rho\pi$ with a branching of 13%, ρ mesons will be produced at ϕ meson factories with a rate that suffices to detect and investigate $\rho^\pm \to \pi^\pm\eta$. The ϕ is furthermore expected to decay into $\eta'\gamma$ with a branching of approximately 10^{-4}. This will presumably be sufficient for detecting and investigating $\eta' \to \rho^\pm\pi^\mp$.

2. Input parameters

We will use the matrix element

$$< \eta|H'|\pi^0 >= -6000 \text{ MeV}^2. \tag{1}$$

We quote two determinations of this value. It firstly follows from the recent determination [3]

$$\frac{m_d - m_u}{m_s} = 1/29 \tag{2}$$

of the quark mass ratios, together with the formula

$$< \eta|H'|\pi^0 >^{tadpole}= -\frac{m_d - m_u}{m_s}(m_K^2 - m_\pi^2)x_P = -6350 \text{ MeV}^2 \tag{3}$$

This assumes the Zweig rule formula

$$_{PS} < s\bar{s}|H'|\pi^0 >= 0 \tag{4}$$

We assume [4] $\theta_P = -20°$ for the pseudoscalar meson mixing angle and have defined

$$|\eta > \;=\; x_P|\frac{u\bar{u} + d\bar{d}}{\sqrt{2}} >_{PS} +y_P|s\bar{s} >_{PS} \tag{5}$$

$$|\eta'> \;=\; -y_P|\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}>_{PS} + x_P|s\bar{s}>_{PS} \tag{6}$$

such that $x_P = 1/\sqrt{3}(cos\theta_P - \sqrt{2}sin\theta_P) \approx 0.822$. We furthermore have

$$<\eta|H'|\pi^0> = <\eta|H'|\pi^0>^{tadpole} + <\eta|H'|\pi^0>^{el.} \tag{7}$$

with [5] $<\eta|H'|\pi_0>^{el.} = 520$ MeV^2 leading to

$$<\eta|H'|\pi^0> = -5800 \text{ MeV}^2. \tag{8}$$

Secondly, [6] has found

$$<\eta|H'|\pi^0> = (-5900 \pm 600) \text{ MeV}^2. \tag{9}$$

In view of the large errors, we neglect the electromagnetic contribution and use the round number in eq.(1) i.e.

$$<\eta|H'|\pi^0> \approx <\eta|H'|\pi^0>^{tadpole} \approx -6000 \text{ MeV}^2 \tag{10}$$

In the same way we assume[1]

$$\begin{aligned} <\eta'|H'|\pi^0> \approx -y_p < \frac{u\bar{u}+d\bar{d}}{\sqrt{2}}|H'|\pi_0>^{tadpole} &= -\frac{y_p}{x_p} <\eta|H'|\pi^0> \\ &= -4200 \text{ MeV}^2. \end{aligned} \tag{11}$$

We will also use [7]

$$<\omega|H'|\rho^0> = (-4520 \pm 600) \text{ MeV}^2. \tag{12}$$

For the ω-ϕ mixing angle the Gell-Mann-Okubo value [4] $\theta_V = 39^\circ$ will be used.

The couplings f_V of the vector mesons ρ, ω, ϕ to the photon are defined such that

$$\Gamma(V \to e^+e^-) = \frac{\pi m_V \alpha^2}{3} f_V^{-2}, \tag{13}$$

[1] We also note that [6] has found $<\eta'|H'|\pi^0> = (-5500 \pm 500)$ MeV^2 for $\theta_P = -13^\circ$. Using eq.(9) together with these numbers one finds that $_{PS}<s\bar{s}|H'|\pi^0> \approx 0$ also in the approach of that reference.

where $\alpha = 1/137$ is the fine structure constant. Numerically $f_\rho^{-2} = 0.16$, $f_\omega^{-2} = 0.014$, $f_\phi^{-2} = 0.024$ in satisfactory agreement with the quark model relation $9:1:2$ for these couplings. As also suggested by the quark model the f_V are assumed to be positive relative to each other.

One of the main ingredients of this work is the vector-vector-pseudoscalar meson coupling constant g defined by the effective Lagrangian

$$L_I = g/2\epsilon_{\alpha\beta\gamma\delta} \sum_{a,b,c=0}^{8} (\partial^\alpha V_a^\beta) V_b^\gamma (\partial^\delta P_c) d_{abc} \tag{14}$$

involving vector meson fields V_a^α with Lorentz-index α, $SU(3)_f$ index a and the pseudoscalar fields P_a. The d_{abc} are the well-known symmetric $SU(3)$ Clebsch-Gordan coefficients, $\epsilon_{\alpha\beta\gamma\delta}$ is the four-dimensional antisymmetric ϵ tensor, and ∂^α is a differentiation symbol. The experimental value of $\Gamma(\rho^0 \to \pi^0\gamma)$ and the width formula

$$\Gamma(\rho^0 \to \pi^0\gamma) = \frac{\alpha g^2}{94 f_\omega^2} \left(\frac{m_\rho^2 - m_{\pi^0}^2}{m_\rho}\right)^3 \tag{15}$$

imply $|g| = 0.0164\ \mathrm{MeV}^{-1}$. This value will be used below.

From the above, widths of the types $P \to \gamma\gamma$, $P \to V\gamma$, $V \to P\gamma$, and $V \to PV$ can be computed in overall agreement with experiment [8, 9, 10]. Details of the results depend on the assumed values of the meson mixing angles and $SU(3)_f$ symmetry breaking corrections and will not concern us here. As examples of straightforward checks of our mixing assumptions, we calculate

$$\begin{aligned}
\Gamma(\rho^0 \to \eta\gamma) &= \frac{\alpha g^2}{96 f_\rho^2} \left(\frac{m_\rho^2 - m_\eta^2}{m_\rho}\right)^3 (x_P)^2 \\
&= 0.174 (x_P)^2 \mathrm{MeV} = 0.119\ \mathrm{MeV}, && (16)\\
\Gamma(\eta' \to \rho^0\gamma) &= \frac{\alpha g^2}{216 f_\rho^2} \left(\frac{m_{\eta'}^2 - m_\rho^2}{m_{\eta'}}\right)^3 (y_P)^2 \\
&= 0.058 (y_P)^2\ \mathrm{MeV} = 0.019\ \mathrm{MeV}, && (17)\\
\Gamma(\phi \to \rho\pi) &= 3\Gamma(\phi \to \rho^0\pi^0) = \frac{g^2}{4\pi} (q(\phi \to \rho^0\pi^0))^3 (x_V)^2 \\
&= 136 (x_V)^2\ \mathrm{MeV} = 0.55\ \mathrm{MeV} && (18)
\end{aligned}$$

and

$$\Gamma(\phi \to \eta\gamma) = \frac{\alpha g^2}{48 f_\phi^2}(\frac{m_\phi^2 - m_\eta^2}{m_\phi})^3 (y_P)^2 = 0.38 (y_P)^2 \text{ MeV} = 0.122 \text{ MeV}. \quad (19)$$

Comparison to the experimental values $\Gamma(\rho^0 \to \eta\gamma) = 0.058$ MeV, $\Gamma(\eta' \to \rho^0\gamma) = 0.059$ MeV, $\Gamma(\phi \to \rho^0\pi^0) = 0.57$ MeV, and $\Gamma(\phi \to \eta\gamma) = 0.057$ MeV indicates the quality of agreement to be expected *without corrections*. In particular, the poor agreement in the only case where $SU(3)_f$ is applied to $s\bar{s}$ states (i.e.$\phi \to \eta\gamma$) invites an $SU(3)_f$ symmetry breaking correction [8]. Overall fits [8, 9, 10] of course also improve the apparent agreement. Theoretical and experimental $\Gamma(\phi \to \rho^0\pi^0)$ compare surprisingly well, lending support to our choise of θ_V.

The width $\Gamma(\phi \to \eta'\gamma)$ can be written in terms of $\Gamma(\phi \to \eta\gamma)$ as

$$\Gamma(\phi \to \eta'\gamma) = (\frac{x_P}{y_P})^2 (\frac{m_\phi^2 - m_{\eta'}^2}{m_\phi^2 - m_\eta^2})^3 \Gamma(\phi \to \eta\gamma) = 5.2 \cdot 10^{-4} \text{ MeV}. \quad (20)$$

The numerical value follows from assuming that η and η' do not mix with mesons outside their $SU(3)_f$ nonet.

3. The decay $\phi \to \pi^+\pi^-$

The observed decays of the $\phi(1020)$ into purly hadronic final states are $\phi \to K\bar{K}$ (Fraction: 0.83), $\rho\pi$ (0.13), $\pi^+\pi^-\pi^0$ (0.024), and $\pi^+\pi^-$ ($8 \cdot 10^{-5}$). This pattern can be understood if the physical ϕ is an almost ideally mixed $s\bar{s}$ vector meson (i.e. $I^G = 0^-$) that decays into $\pi^+\pi^-$ electromagnetically (Fig.1c) as well as hadronically via an isospin symmetry violating mixing with ρ^0 (Fig.1b). More specifically, we assume the resonant part A_ϕ of the invariant $< \gamma|\pi^+\pi^- >$ amplitude (Fig.1a) around $\sqrt{s} = 1020$ MeV to be given by Fig.1b and 1c. The total amplitude

$$A(s) = F_\pi(s) + A_\phi(s) \quad (21)$$

also contains a non-resonant smooth interpolation $F_\pi(s)$ of the total formfactor A of the π over the ϕ resonance region. As an illustrative examle we will saturate $F_\pi(s)$ by the Breit-Wigner propagator of the ρ in the normalization $F_\pi(m_\rho^2) = 1/i\Gamma_\rho m_\rho$ such that

$$F_\pi(s) = \frac{1}{s - m_\rho^2 + i\Gamma_\rho m_\rho}. \quad (22)$$

Since $A_\phi(m_\rho^2) \approx 0$, we also have $A(m_\rho^2) \approx F_\pi(m_\rho^2) = 1/i\Gamma_\rho m_\rho$. From Figs. 1b and 1c we read off

$$A(s) = F_\pi(m_\phi^2) + \frac{f_\rho}{f_\phi}\frac{m_\phi^2}{m_\rho^2}\frac{1}{s - m_\phi^2 + i\Gamma_\phi m_\phi}[\frac{x_V < \omega|H'|\rho^0 >}{s - m_\rho^2 + i\Gamma_\rho m_\rho} + \frac{\alpha\pi}{f_\phi f_\rho}F_\pi(m_\phi^2] \tag{23}$$

for $s \approx m_\phi^2$. In analogy to the pseudoscalar case we have defined $x_V = 1/\sqrt{3}(cos\theta_V - \sqrt{2}sin\theta_V)$.

A few comments are in order. Since the hadronic isospin symmetry breaking Hamiltonian is proportional to $(u\bar{u} - d\bar{d})$, the ϕ couples hadronically to the ρ via ϕ-ω mixing only. This yields the factor x_V. The contribution of $\omega \to \gamma \to \rho^0$ is contained in $< \omega|H'|\rho^0 >$. The contribution of the ρ^0 at $\sqrt{s} \approx m_\phi$ is then parametrized by the Breit-Wigner propagator. This is entirely correct for the hadronic ω-ρ^0 transition. For the photonic transition $\omega \to \gamma \to \rho^0$ it may be argued that the coupling is to $F_\pi(m_\phi^2)$ rather than to the Breit-Wigner ρ^0. It is however easy to see that the photonic contribution to $< \omega|H'|\rho^0 >$ is small. Namely, the contribution of $\omega \to \gamma \to \pi^-\pi^+$ to $\omega \to \pi^-\pi^+$ can be read off an obvious modification of eq.(23). If there were no other contribution, $\Gamma(\omega \to \pi^-\pi^+) = 0.005$ MeV (whereas the experimental width is 0.19 MeV). We follow [11] in factorizing the $< \gamma|\pi^+\pi^- >$ amplitude in the neighbourhood of the $\phi(1020)$ such that the s dependent factor containing the ϕ resonance reads

$$1 + Q\frac{e^{i\psi}m_\phi\Gamma_\phi}{s - m_\phi^2 + im_\phi\Gamma_\phi} = 1 + \frac{f_\rho}{f_\phi}\frac{m_\phi^2}{m_\rho^2}\frac{Y}{s - m_\phi^2 + im_\phi\Gamma_\phi}, \tag{24}$$

where Y is given by

$$Y = \frac{\alpha\pi}{f_\rho f_\phi}m_\rho^2 + |\frac{F_\pi(m_\rho^2)}{F_\pi(m_\phi^2)}|\frac{m_\rho\Gamma_\rho x_V < \omega|H'|\rho^0 >}{m_\phi^2 - m_\rho^2 + i\Gamma_\rho m_\rho}e^{iR}, \tag{25}$$

with R the phase of $F_\pi(m_\phi^2)$ at the ϕ resonance

$$F_\pi(m_\phi^2) = |F_\pi(m_\phi^2)|e^{-iR}. \tag{26}$$

Assuming for m_ϕ and Γ_ϕ the values of [4] $m_\phi = 1019.4$ MeV and $\Gamma_\phi = 4.43$ MeV, respectively, the observables to be determined experimentally are

ψ and

$$Q = [\frac{36B(\phi \to \pi^-\pi^+)B(\phi \to e^-e^+)}{\alpha^2(1-4m_\pi^2/m_\phi^2)^{3/2}|F_\pi|^2}]^{1/2}. \tag{27}$$

Ref.[11] finds

$$\psi = (20 \pm 13)^\circ \tag{28}$$

together with

$$Q = 0.07 \pm 0.02. \tag{29}$$

Using, as has also been obtained in[11], $|F_\pi|^2 = 2.9 \pm 0.2$ and $B(\phi \to e^-e^+) = 3 \cdot 10^{-4}$ this yields

$$\Gamma(\phi \to \pi^+\pi^-) = 2.8 \cdot 10^{-4} \text{ MeV}. \tag{30}$$

The value $\Gamma(\phi \to \pi^+\pi^-) = (3.5 \begin{array}{c} +2.2 \\ -1.8 \end{array}) \cdot 10^{-4}$ MeV [4] combines this result with the much higher $\Gamma(\phi \to \pi^+\pi^-) = 8 \cdot 10^{-4}$ MeV of ref.[12]

Using R as a parameter, our results are presented in Table 1. Approximate agreement with experiment is obtained for R between -170° and 15°. A more meaningful test will hopefully be provided by DAΦNE.

4. The decay $\phi \to \omega\pi^0$

The amplitude $< \phi|\omega\pi^0 >$ is determined by the contributions of Fig.2. We emphasize that, other than in Fig. 1c, we have in Fig.2c *only to take the contribution of the* $\rho^0(770)$ into account, i.e. *not* the full $F_\pi(M_\phi^2)$. Namely interpreting $F_\pi(s)$ in the neighbourhood of the $\phi(1020)$ as the *sum* of the contributions of the $(I = 1)$ vector mesons $\rho(770)$, $\rho(1450)$, and $\rho(1700)$, the Meson Full Listings of Ref.[4] suggest that *only the* $\rho(770)$ *considerably couples to* $\omega\pi^0$. Thus we may write for the amplitude (taking the $\rho^0\omega\pi^0$ coupling from Sect.2 rather than directly from the Gell-Mann-Sharp-Wagner calculation [10, 13] of $\omega \to 3\pi$)

$$A = \sum_{j=a}^{e} A^{(j)} \tag{31}$$

with

$$A^{(a)} = \frac{gx_V < \omega|H'|\rho^0 >}{m_\omega^2 - m_\rho^2 + im_\rho\Gamma_\rho}, \tag{32}$$

$$A^{(b)} = \frac{g x_V < \omega|H'|\rho^0 >}{m_\phi^2 - m_\rho^2 + i\Gamma_\rho m_\rho}, \tag{33}$$

$$A^{(c)} = \frac{\alpha g \pi m_\rho^2}{f_\phi f_\rho} \frac{1}{m_\phi^2 - m_\rho^2 + i\Gamma_\rho m_\rho}, \tag{34}$$

$$A^{(d)} = x_V g [x_P \frac{< \eta|H'|\pi^0 >}{m_{\pi^0}^2 - m_\eta^2} - y_P \frac{< \eta'|H'|\pi^0 >}{m_{\pi^0}^2 - m_{\eta'}^2}] \tag{35}$$

and

$$A^{(e)} = \sqrt{2} x_V g [y_P \frac{< \eta|H'|\pi^0 >}{m_{\pi^0}^2 - m_\eta^2} + x_P \frac{< \eta'|H'|\pi^0 >}{m_{\pi^0}^2 - m_{\eta'}^2}] \tag{36}$$

The width is

$$\Gamma(\phi \to \omega\pi^0) = |A|^2 \frac{(q(\phi \to \omega\pi^0))^3}{12\pi} \tag{37}$$

The input parameters we use yield $\Gamma(\phi \to \omega\pi^0) = 4 \cdot 10^{-4}$ MeV.

5. The decays $\rho^\pm \to \pi^\pm\eta$ and $\eta' \to \rho^\pm\pi^\mp$

Finally we consider the decays $\rho^\pm \to \pi^\pm\eta$ and $\eta' \to \rho^\pm\pi^\mp$. They obviously violate G parity and thus isospin symmetry (since charge conjugation symmetry holds for these strong and/or electromagnetic decays). The strong isospin symmetry conserving matrix element leading to the proposed decays via $\pi^0\eta$ and $\pi^0\eta'$ mixing, is in both cases $< \rho^\pm\pi^\mp\pi^0 >$.

With q the decay momenta of the P-wave decays we thus obtain

$$\Gamma(\rho^+ \to \pi^+\eta) = [\frac{q(\rho \to \pi\eta)}{q(\rho \to \pi\pi)}]^3 \cdot [\frac{< \eta|H'|\pi^0 >}{m_\pi^2 - m_\eta^2}]^2 \cdot \Gamma(\rho^+ \to \pi^+\pi^0) = 4 \cdot 10^{-3} \text{ MeV} \tag{38}$$

and, taking both final charge states together

$$\Gamma(\eta' \to \rho^\pm\pi^\mp) = 2 \cdot 3 \cdot [\frac{q(\eta' \to \rho\pi)}{q(\rho \to \pi\pi)}]^3 \cdot [\frac{< \eta'|H'|\pi^0 >}{m_\pi^2 - m_{\eta'}^2}]^2 \cdot \Gamma(\rho^+ \to \pi^+\pi^0)$$
$$= 7 \cdot 10^{-4} \text{ MeV}. \tag{39}$$

The factor 3 in the second formula is due to the summation (rather than averaging) over the spin orientations of the ρ. The results for the branching ratios BR are $BR(\rho^+ \to \pi^+\eta) = 3 \cdot 10^{-5}$ and $BR(\eta' \to \rho^\pm\pi^\mp) = 4 \cdot 10^{-3}$,

leading to branchings $BR[\phi \to \rho^{\pm}\pi^{\mp} \to (\pi^{\pm}\eta)\pi^{\mp} \to (\pi^{\pm}\gamma\gamma)\pi^{\mp}] = 10^{-6}$ and $BR[\phi \to \eta'\gamma \to (\rho^{\pm}\pi^{\mp})\gamma] = 2 \cdot 10^{-6}$. Thus meaningfull conclusions on these decays can be obtained at ϕ meson factories [14].

6. Conclusions

In conclusion we note that our understanding of the processes considered here and those connected to them by $SU(3)_f$ symmetry, vector meson dominance, and isospin symmetry breaking will be strongly enhanced by accurate e^-e^+ annihilation experiments in the $\phi(1020)$ resonance region. As to orders of magnitude, mainstream low energy phenomenology can accomodate the observed $\psi = (-20 \pm 13)^\circ$ and $Q = 0.07 \pm 0.02$ within the large experimental errors. Our input data favor a ψ that is negative and nearer to 0° and/or a larger Q (implying a larger $\Gamma(\phi \to \pi^-\pi^+)$). The width $\Gamma(\phi \to \omega\pi^0)$ is predicted to be approximately $4 \cdot 10^{-4}$ MeV. Our predictions concerning $\rho^{\pm} \to \pi^{\pm}\eta$ and $\eta' \to \rho^{\pm}\pi^{\mp}$ are stated at the end of the previous section.

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Figure Captions

Fig.1. Diagrams used to compute ψ and Q of $e^-e^+ \to \pi^-\pi^+$ near the $\phi(1020)$ resonance.

Fig.2 Diagrams used to compute the width $\Gamma(\phi \to \omega\pi^0)$

Table 1. Using R of eq.(26) as parameter, the predicted values of ψ and Q (eq.(27)) are listed and compared to experiment [11].

Condition	R (degree)	ψ (degree)	Q
Experiment		-20 $\pm$ 13	0.07$\pm$0.02
Destructive interference	-165.7	0	0.089
	-150	-6.4	0.091
	-120	-15	0.10
Phase ψ minimal	-93	-17	0.12
Consructive interference	14.3	0	0.16
Phase ψ maximal	122	17	0.12